Gaia Follow-up projects: the power of spectroscopy

A. Vallenari

INAF, Padova

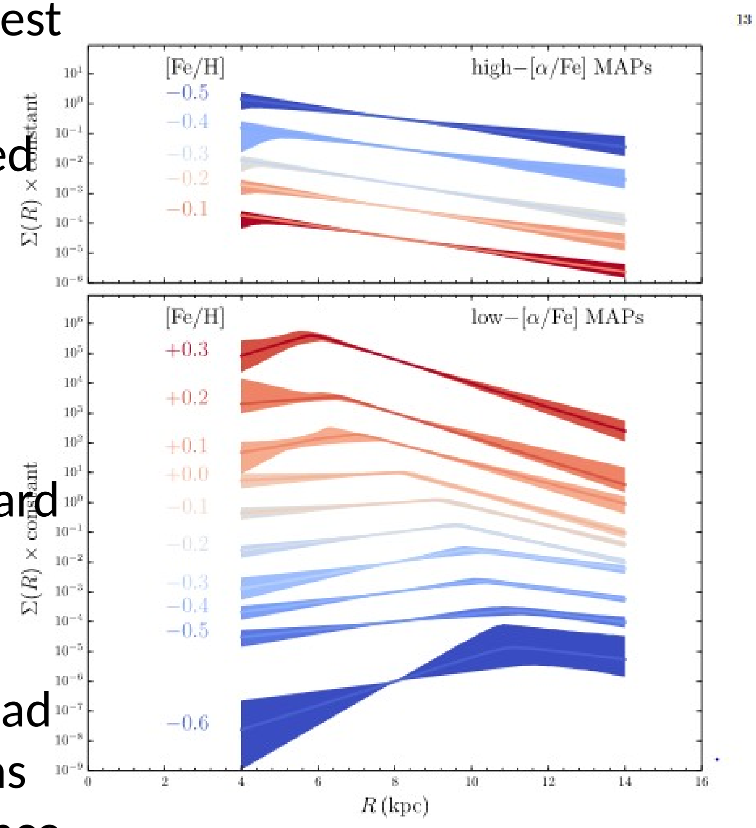
Overview

- The power of Gaia and Spectroscopic follow-up
- GES
- WEAVE

→ Many talks/posters during this week about other surveys and GES specific aspects (Jeffries, Smiljanic, Lanzafame, Casamiquela, Sacco…)

The Galaxy view

- Unveiling the complex history of the MW assembly and internal evolution is still one of the main interest of astrophysics
- However the specific questions we ask have evolved substantially
- Diagnostics: Kinematics + chemistry of stars+ distance+ ages
- Metallicity from photometry /spectroscopy
- Large amount of data requires ad-hoc modeling: hard to separate the different components
- The selection function importance
- The presence of radial migration in the disks has lead to a different way of describing stellar populations using chemical abundances as tag: Mono-abundance vs mono-age populations (Bovy+2016, Minchev 2017)
- Data driven models (Anderson + 2017, Leistedt+2017)



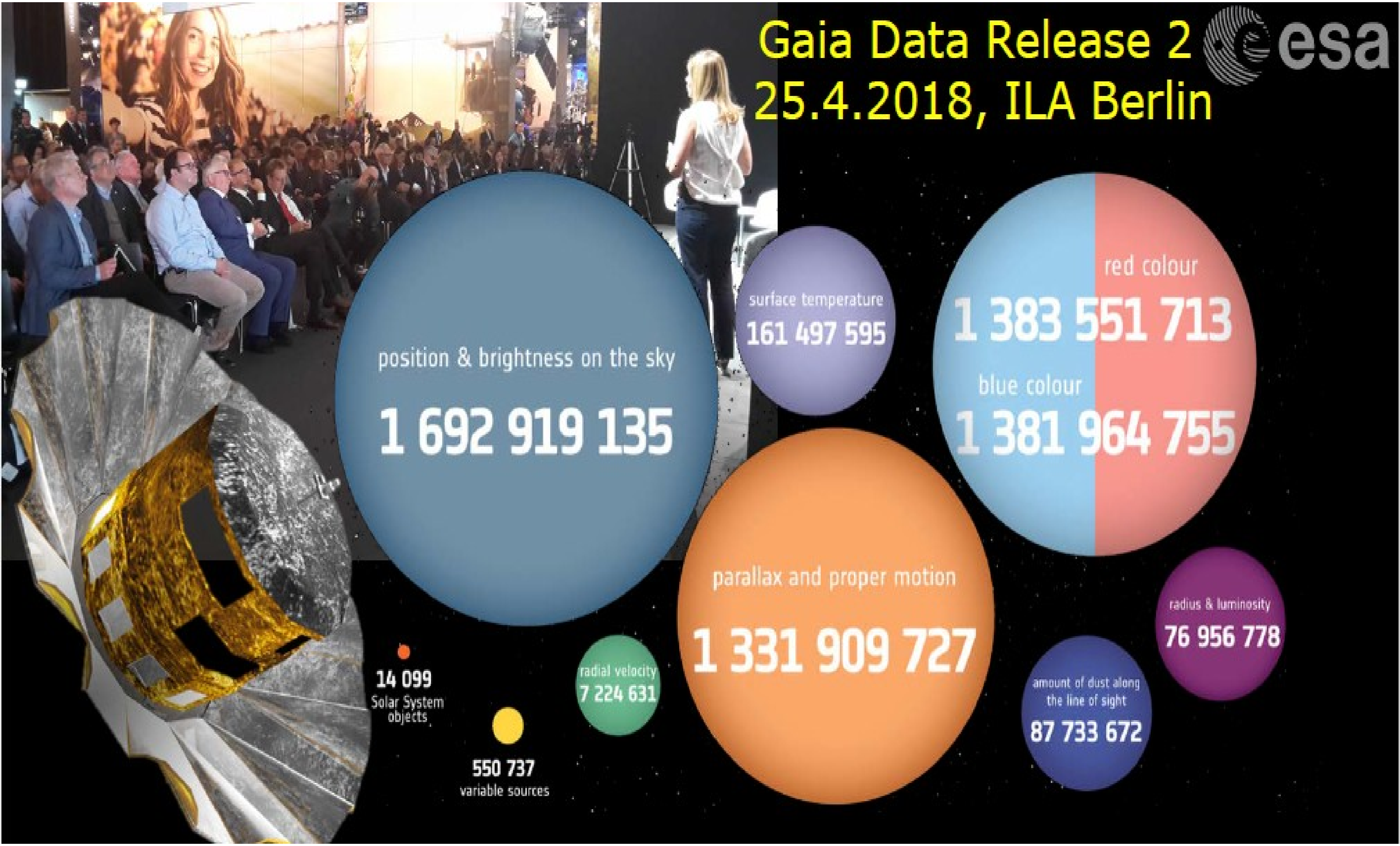
Bovy et al 2016

MW key questions

Structure formation on sub-galactic scale

- **Halo**: variation of halo properties with distance from the center (Deason, Belokurov & Evans 2011; Ablimit & Zhao 2018, Fernandez-Alvar et al. 2015, Carollo et al. 2007, 2010; Beers et al. 2012)
  - in situ vs accreted(Font et al. 2011; Tissera et al. 2012, 2013,2014, Nissen & Schuster 2010, Hayes et al 2018, Helmi et al 2017, Fernandez_Alvar 2018)
  - What is the total mass of the Milky Way? What is the shape of the Galactic gravitational potential? (Battaglia + 2015, Koposov+ 2009)
  - Where   are the most metal-poor stars in the Milky Way, what are their properties, and what do they tell us about the physics of the early Universe? (Caffau+2011)
  - dSph and UDFs : the role of disrupted dwarfs (Fabrizzio+2015, Tolstoy+2009)
- **Disks:** respective roles of hierarchical formation and secular evolution in shaping the Galaxy? what are the roles of spirals (+ number of arms, pitch angle, pattern speed?) and the bar (length, pattern speed?) (Helmi+2006, Schoenrich & Binney 2009, Minchev+2015)
- **Dark matter :** How much substructure does the Galactic dark matter distribution have with: in 20−50 kpc? How do they interact with cold streams? (Yoon + 2011)

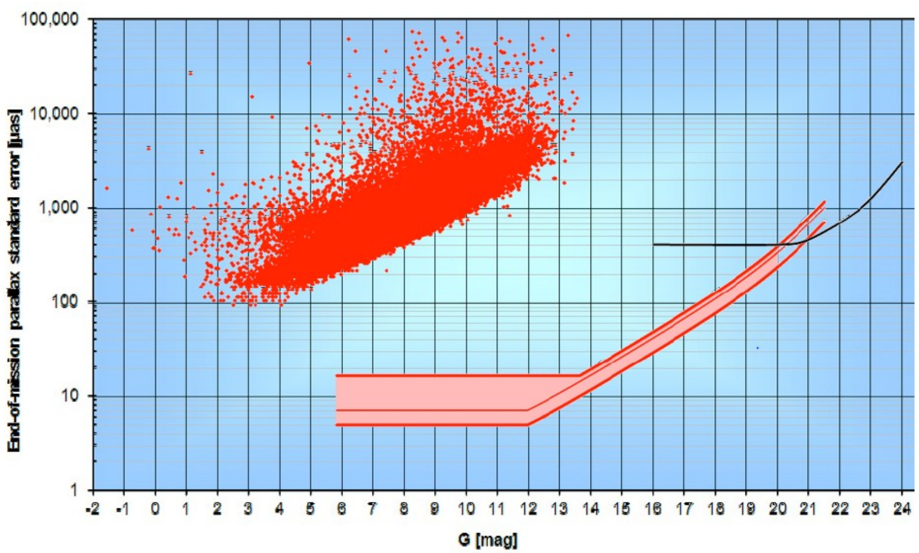
The Gaia revolution

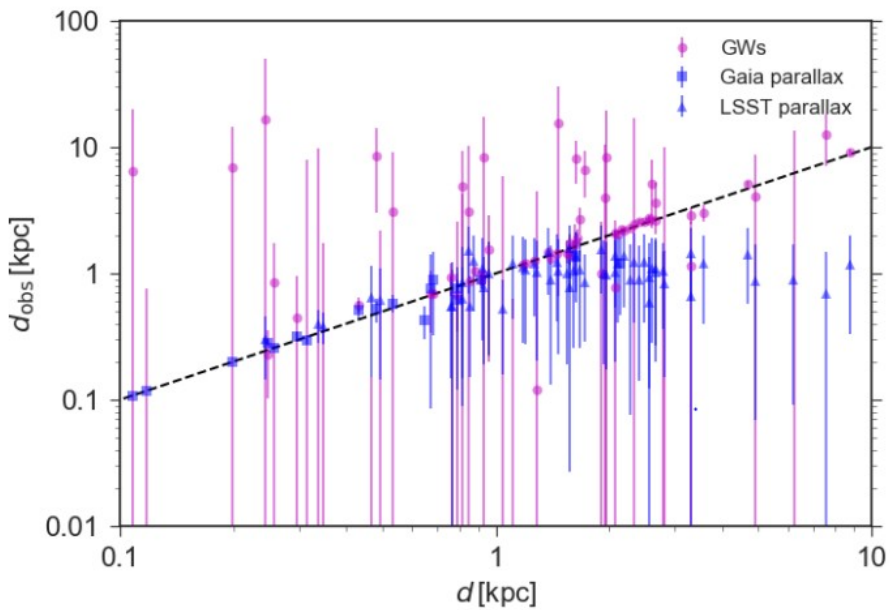


Gaia Collaboration, Brown Vallenari et al 2018

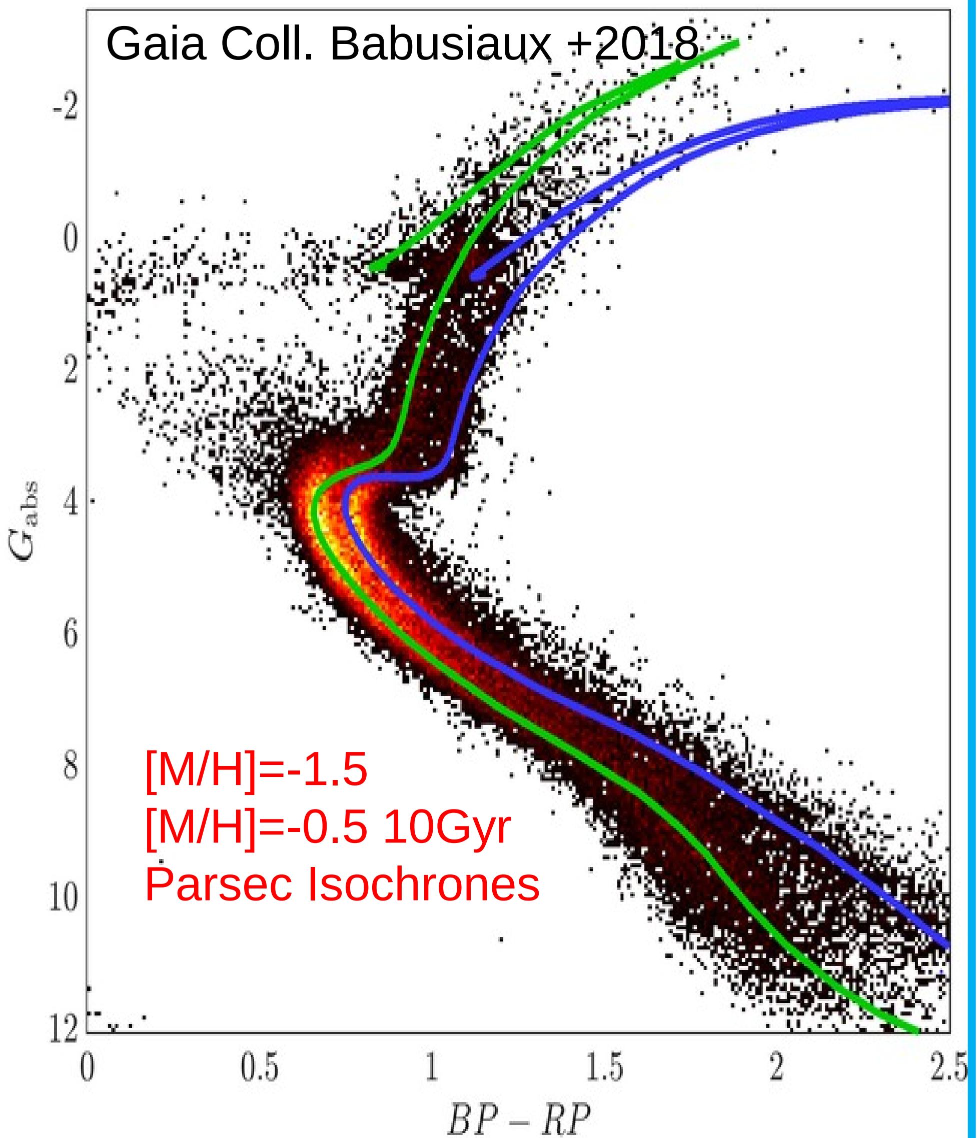
Galactic Archeology

- A wealth of information from ground and space based and surveys
  - **Pan-STARRS** (Kaiser+2010, δ>-30, no u filter), **Sky mapper**(Keller 2012)
  - **Gaia, LSST** (Ivezic+ 2014, 2022, r=24.5, 30,000sq deg), **PLATO, TESS**
  - **Lisa,Gaia,LSST**: 100,000 ultra-compact binary WDs to trace the barionic mass in disk and bulge (Korol 2018)
- Spectroscopic surveys: GES, RAVE, APOGEE, GALAH, SDSS, SEGUE, Lamost, 4MOST, MOONS, WEAVE...

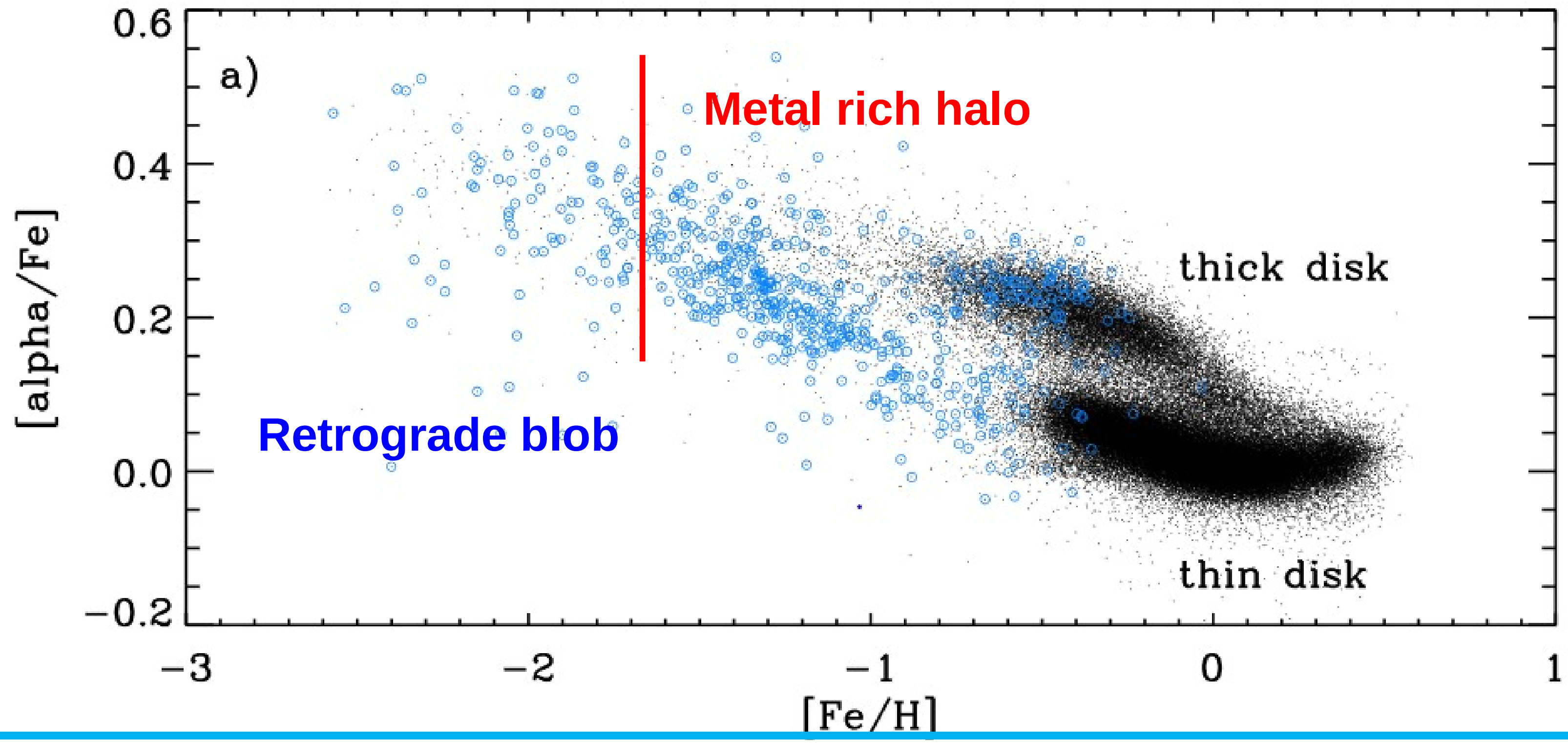




Gaia DR2 new view of the Halo



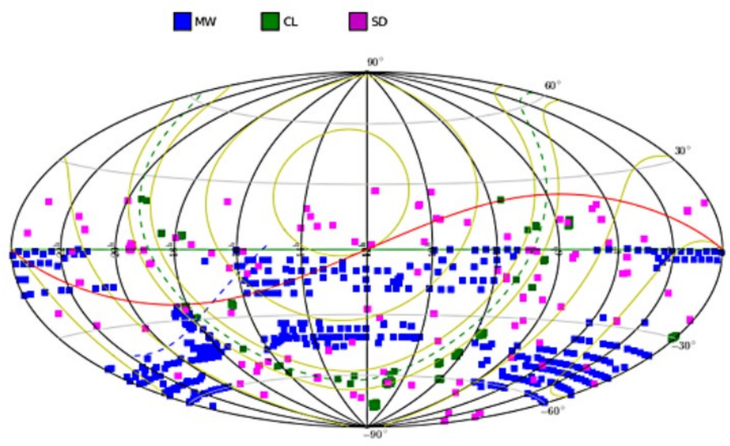
- Kinematically selected halo stars having [Fe/H] > -1 (Bonaca +2017)
- Local Halo merging history from TGAS+ RAVE (Helmi 2017, Myeong+2017
- Accretion events with DR2 found in the halo using a variety of data (Belokurov et al. 2018; Myeong et al. 2018a,b; Deason et al. 2018; Kruijssen et al 2018,Koppelman+ 2018, Lancaster+2018…)
- Haywood +2018: using Nissen &Schuster metallicity confirm that red sequence is thick disk
- Gaia Sausage/Enceladus retrograde stars are on the blue sequence(Helmi+2018)



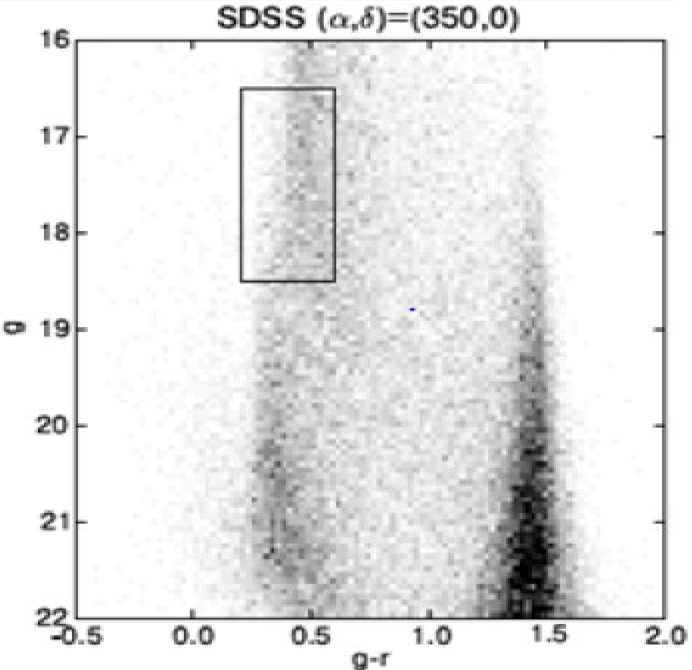
- Gaia+SDSS data : Gaia Sausage contributing to 50% mass of the halo within 25 Kpc (Belokurov+2018, Lancaster+2018, Kruijssen+2018)
- 100,000 stars DR2+APOGEE within 5 Kpc (Helmi+ 2018)
- In the inner 30 Kpc the stellar halo could be largely dominated by a single, ancient, extremely radial merger 10 Gyr ago
- [alpha/FeH] different from thick disk: long lasting SF
- High mass progenitor :10 $^{9-10}$ Mo

GES in a nutshell

- GIRAFFE :R=16000-25000
  - Bulge: mostly giant stars (clump and RGB), I=15
  - Halo /thick disc: FG TO stars (17 < r < 18);
  - Thin disc – RVs for dynamics; I<19
- UVES parallel R=42,000 SNR > 20 SN: unbiased 5000- star sample.
  - Mv~5.5, ➔ unbiased survey to 1kpc at V=15
- 60-70-Ocs in UVES (V<16): GIRAFFE (G <19)



Map of observed targets on the sky (provided by Cambridge Astronomy Survey Unit (CASU), see Gaia-ESO Survey overview). Observations included in the fifth internal Survey data release (iDR5; from the beginning of the Survey up until December 2015) are shown. **Key:** MW = Milky Way, CL = Cluster, SD = Standard.



The challenge

- 5 groups of people using different analysis methods (EW, spectral synthesis)→15 pipelines (Smiljanic+2014, Lanzafame+2015)
  - (MATISSE, SME: Valenti & Piskunov1996; FERRE: Allende Prieto et al. 2006 codes for GIRAFFE spectra, and about a dozen different methods for UVES spectra)
- More methods means more information
- Common line list (Heiter+ 2015, Heiter +in preparation)
- Common stellar models (MARCS)
- Selection function vs Vista HS Stonkute et al. (2016)
- Set of calibration objects(Pancino+2017)
  - to Identify the dominant systematic variables
  - to identify both systematic method errors and random errors
  - Add seismic data for precision and systematics
  - Share calibration across all the Surveys
- Calibrators: RV standards;Gaia benchmark stars (Jofre'2014, Hawkins+2016); Clusters: (20) hot vs. cool; PMS vs. MS vs. evolved;
  - CoRoT –Kepler asteroseismic gravities and ages

RAVE EXTERNAL COMPARISONS BY SURVEY

		AlgoConv $\neq 1$	AlgoConv $= 0$, SNR < 50	AlgoConv $= 0$, SNR > 50
APOGEE	$T_{\rm eff}$:	-30 ± 277	4 ± 342	-75 ± 107
	$\log g$:	-0.22 ± 0.60	-0.35 ± 0.70	-0.05 ± 0.37
	[Fe/H]:	0.08 ± 0.44	0.05 ± 0.52	0.16 ± 0.14
	Num:	711	190	221
	$\log g_{sc}$:	0.03 ± 0.29	0.06 ± 0.31	0.00 ± 0.27
	$\mathrm{Num_{sc}}$:	317	129	184
GAIA-ESO	$T_{\rm eff}$:	243 ± 477	613 ± 659	52 ± 266
	$\log g$:	-0.12 ± 0.89	-0.82 ± 0.91	0.08 ± 0.46
	[Fe/H]:	0.25 ± 0.93	-0.10 ± 0.30	0.13 ± 0.21
	Num:	53	11	28
	$\log g_{sc}$:	0.17 ± 0.64	0.19 ± 0.35	0.16 ± 0.69
	$\mathrm{Num_{sc}}$:	18	3	15
Clusters	$T_{\rm eff}$:	38 ± 309	-62 ± 422	106 ± 244
	$\log g$:	-0.12 ± 0.63	-0.42 ± 1.13	0.13 ± 0.29
	[Fe/H]:	-0.10 ± 0.28	-0.21 ± 0.39	0.01 ± 0.16
	Num:	75	15	26
	$\log g_{sc}$:	-0.39 ± 0.45	-0.59 ± 0.29	-0.17 ± 0.50
	$\mathrm{Num_{sc}}$:	14	6	7
Misc. Field Stars	$T_{\rm eff}$:	126 ± 397	251 ± 517	111 ± 196
	$\log g$:	-0.05 ± 0.95	-0.33 ± 1.17	0.15 ± 0.51
	[Fe/H]:	-0.09 ± 0.40	-0.17 ± 0.48	0.01 ± 0.18
	Num:	317	57	169
	$\log g_{sc}$:	-0.25 ± 0.90	-0.37 ± 0.95	-0.18 ± 0.90
	$\mathrm{Num_{sc}}$:	51	16	33
LAMOST	$T_{\rm eff}$:	30 ± 325	-4 ± 364	58 ± 208
	$\log g$:	0.12 ± 0.48	0.08 ± 0.49	0.16 ± 0.36
	[Fe/H]:	0.05 ± 0.27	0.00 ± 0.27	0.09 ± 0.15
	Num:	2700	2026	987
	$\log g_{sc}$:	0.14 ± 0.40	0.24 ± 0.45	0.06 ± 0.33
	$\mathrm{Num_{sc}}$:	557	224	313
GALAH	$T_{\rm eff}$:	-36 ± 274	-43 ± 376	-6 ± 144
	$\log g$:	0.0 ± 0.50	-0.02 ± 0.59	0.06 ± 0.35
	[Fe/H]:	-0.02 ± 0.33	-0.07 ± 0.45	0.04 ± 0.13
	Num:	1700	526	663
	$\log g_{sc}$:	0.04 ± 0.45	0.0 ± 0.56	0.06 ± 0.32
	$\mathrm{Num_{sc}}$:	1255	443	613

Kunder+2017

Disk Vertical metallicity gradient

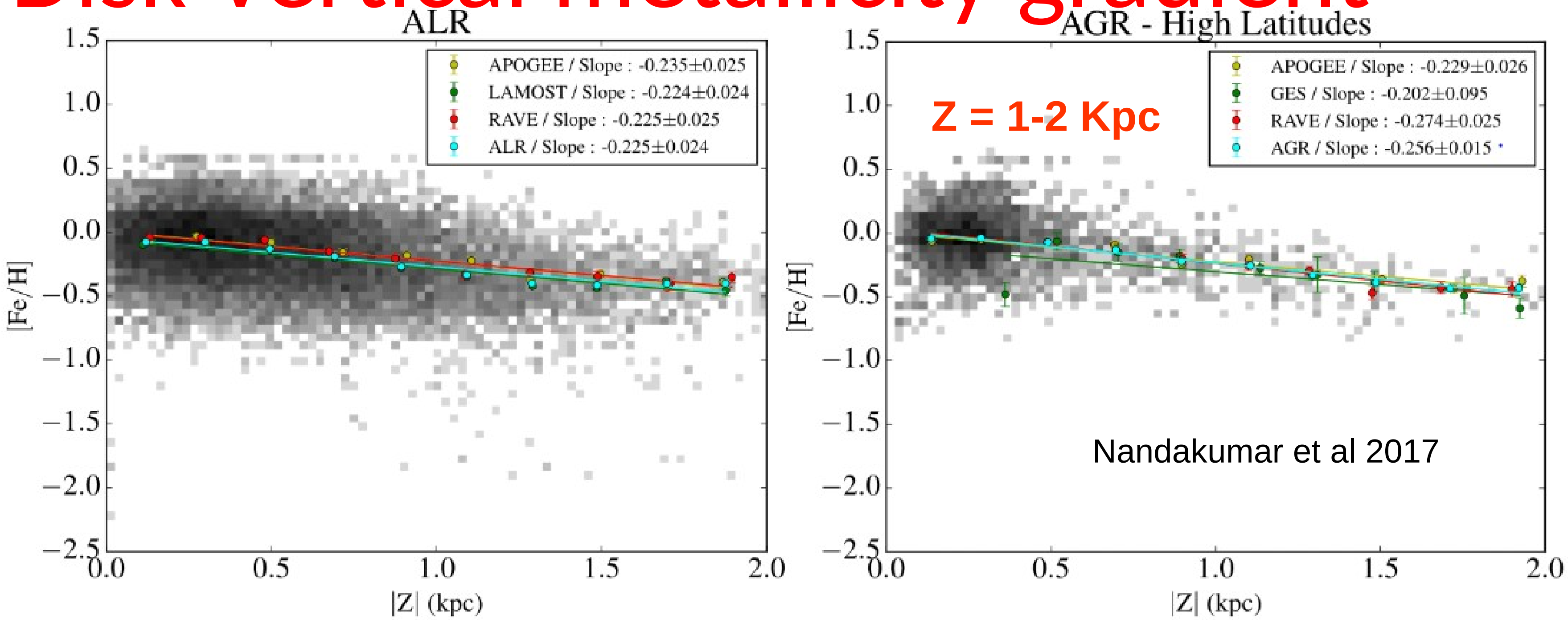


Fig. 11. Vertical metallicity gradients calculated for all sources in each survey belonging to ALR (left) and AGR (right). The slope estimated for each survey is also shown in the plots. The gradient for the combined sample of surveys is shown for ALR and AGR.

- Indication of formation model (disk heating spiral arms and mergers)
  (Chiappini+2001, Schoenrich 2009, Rix &Bovy 2013…)
- Agreement between different surveys and with Schlesinger et al. 2014,
  Xiang 2015,Cheng 2003, Duong 2018 (GALAH)
- Boeche et al. (2014) -0.112±0.007 dex kpc RAVE Z<2kpc
- Soubiran et al. (2008): -0.31±0.03 dex/ kpc

Bulge

- Several papers supporting the boxy/peanut X-shaped component in the metal-rich population, with bar-like kinematics (Rojas-Arriagada+2014 Williams+2016)
- Low-Alpha stars found in the Bulge with chemical pattern similar to thin disk. A thin disk contribution to the Bulge?(Recio-Blanco+2017)
- Two populations from large sample of high resolution spectroscopy (Babusiaux 2010, but see Ness 2013)
- vertical metallicity gradients in both
- Metal rich has a bar-like kinematics and consistent with X-shape→overlap with thin disk in [Mg/Fe]vs [FE/H]→ formed by secular evolution of the thin disk
- Metal poor has isotropic kinematics and no X-shape
- Confirmed recently Schultheis+2017 (APOGEE)

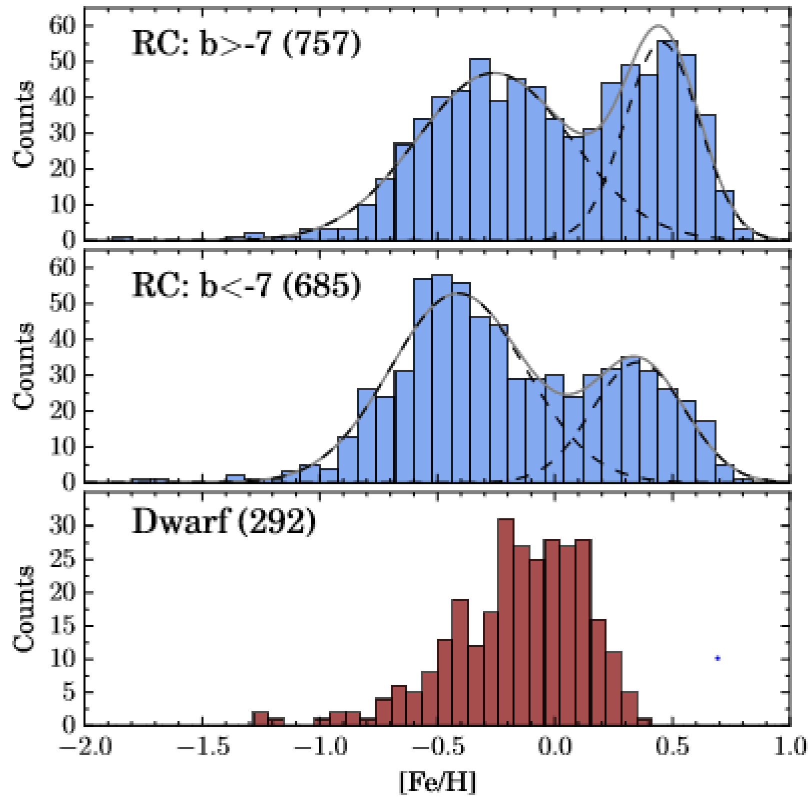
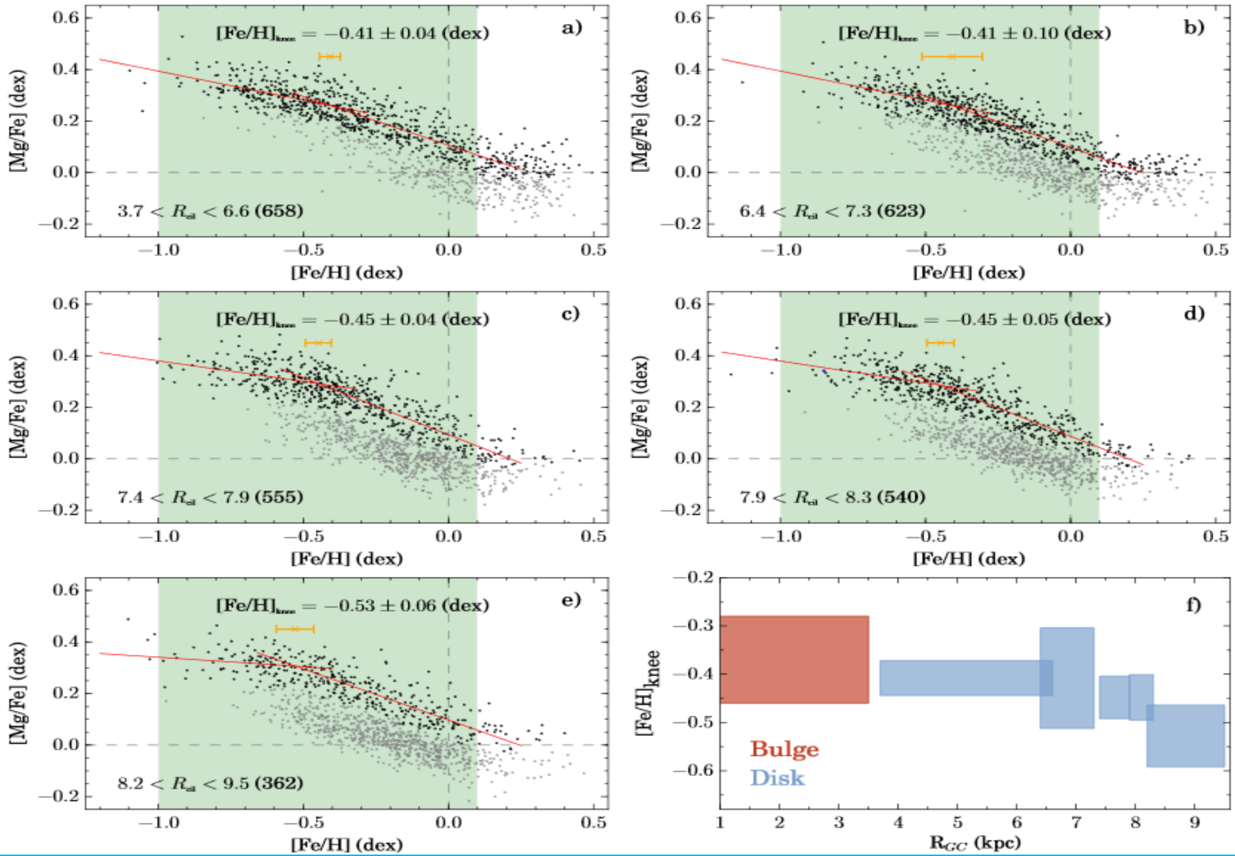


Fig. 6. *Upper panel:* Combined MDF of fields located close to the Galactic plane ($b > -7°$). *Middle panel:* Combined MDF of fields located far from the Galactic plane ($b < -7°$). The individual GMM components are drawn with black dashed lines, while their combined profile as a solid gray line. *Lower panel:* MDF of stars classified as dwarfs according to their $\log g$ values. In all panels, the total number of stars is indicated in parentheses.

Rojas-Arriagada +2014, 2017

Thin/Thick disk



Rojas-Arriagada 2017

- Discreteness of thin/thick disk in elemental abundances
- in agreement with APOGEE (Hayden +2015)
- Thin/thick disk intersect at solar metallicity
- The knee is constant with RGC→ thick disk formed in a single episode, not inside-out

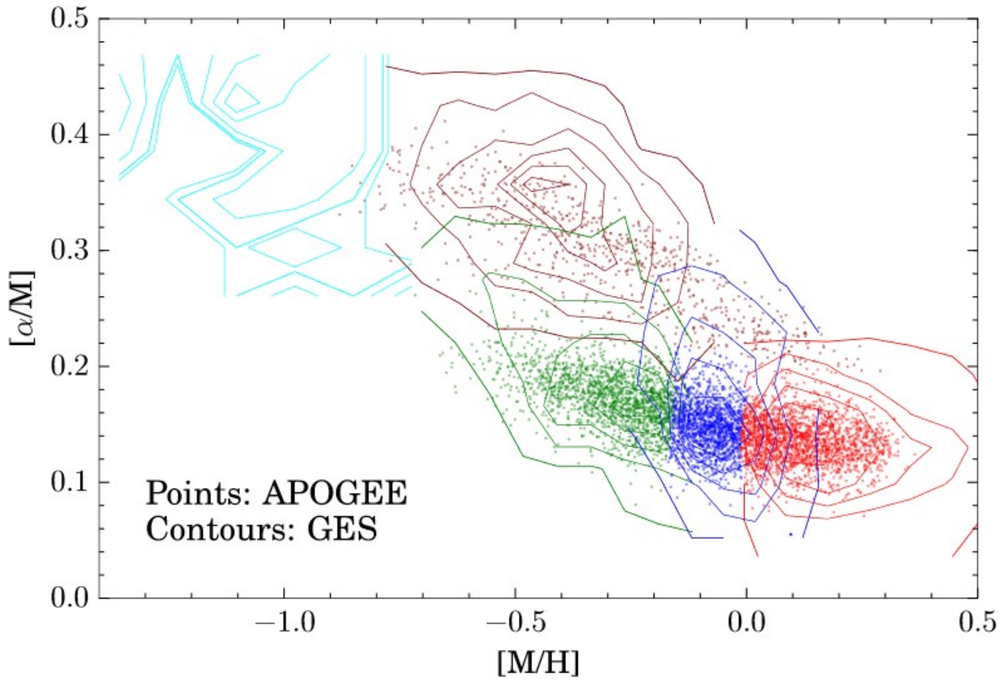


Fig. 3. GMM decomposition of Gaia-ESO survey and APOGEE samples in the $[\alpha/M]$ vs. [M/H] plane. Points depict the APOGEE working sample. Contour lines draw the density distribution of Gaia-ESO survey GMM data groups. A vertical shift of $\Delta[\alpha/M] = 0.1$ dex was applied to the APOGEE sample to obtain a better agreement between the two data

- Three sub-populations in the thin disk
- Different spatial and kinematical properties of the metal poor component
- Mild increase of overall chemical and dynamical properties between the groups is smooth suggesting a mild early disk evolution

and inside-out scenario

Rojas-Arriagada+2016

Thin disk OC radial gradient

- Radial metallicity gradient in the inner disk
- From 12 Ocs: -0.10 ± 0.02 dex kpc(Jacobson+2016)
- Old Ocs in SV have higher [Fe/H] than the younger ones
- super-metal-rich stars in the Solar V. (Minchev+2013; Anders +2016)
- Migrations? (Schönrich & Binney 2009; Minchev et al. 2010, Anders 2017, Quillen 2018)

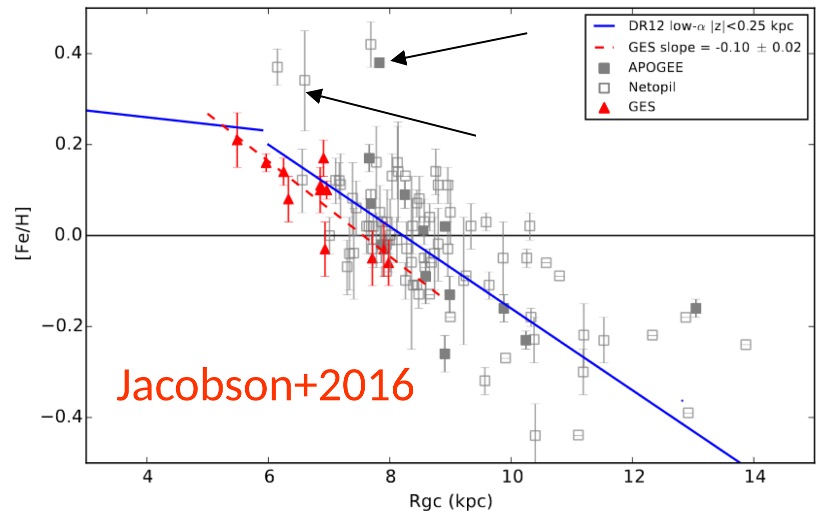
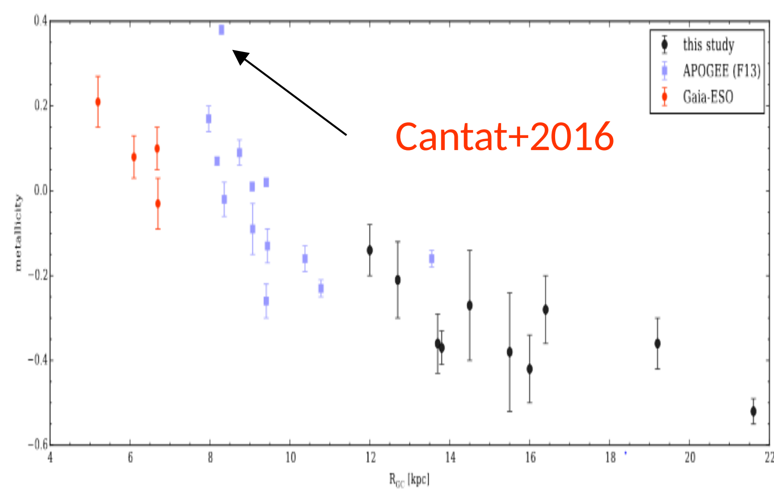


Fig. 2. Metallicity gradient as shown by the GES open clusters (red



Inner disk metallicity gradient

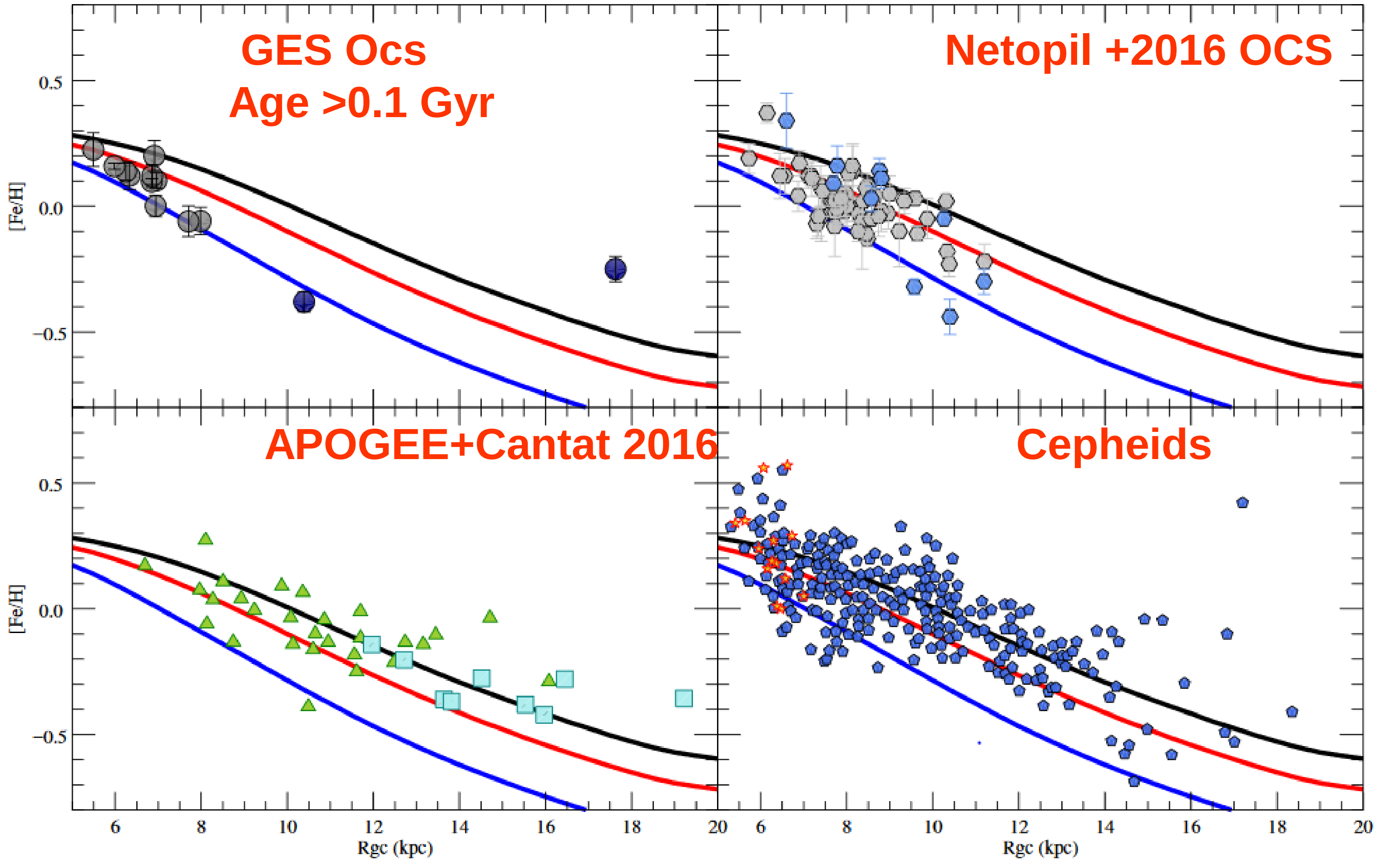
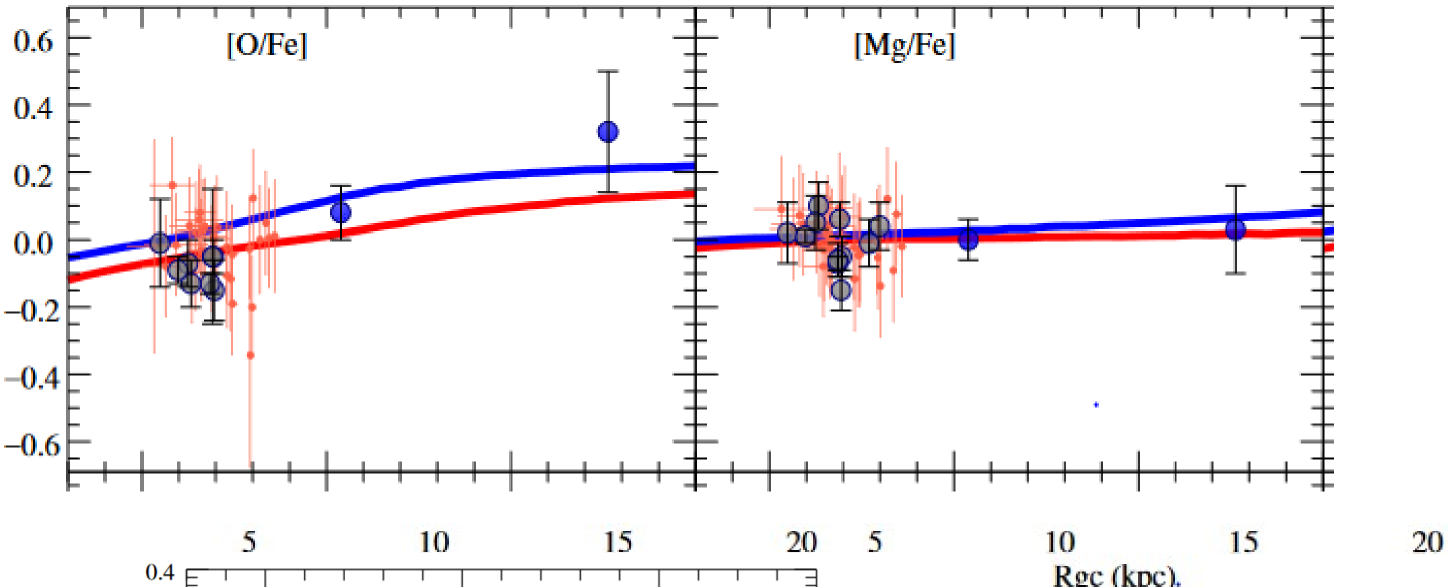


Fig. 5. Radial distributions of [Fe/H] for our open cluster sample (*first panel*: filled circles in grey the youngest clusters, age < 2 Gyr, and in blue the oldest ones), for the Netopil et al. (2016)'s open clusters with high-resolution metallicities (*second panel*: filled hexagons in grey the youngest clusters, age < 2 Gyr, and in blue the oldest ones), for the APOGEE (Cunha et al. 2016) and Cantat-Gaudin et al. (2016)'s open clusters (*third panel*: green triangles and cyan squares, resepctively), and for the Cepehids (*fourth panel*: stars and pentagons Martin et al. 2015; Genovali et al. 2014, 2015, respectively). The black curves represent the gradients of the elements over Fe in the K15-improved model at the present time – updated with the new yields of the present work – while the red and blue ones corresponds to 2 Gyr and 5 Gyr ago, respectively.

Magrini+ 2017 GES data Kubryk+2015 models (radial flow, migration)

Radial metallicity gradient



Magrini + 2017

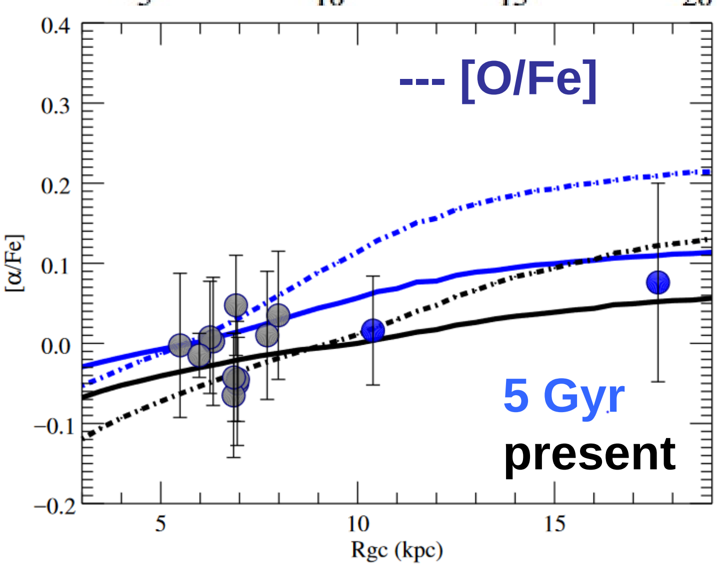


Fig. 8. Global α-enhancement: [α/Fe] vs. R_{GC} in the open cluster observations (colour coded by age as in Fig. 6) and in the K15-improved model (continuous lines, black at the present time and blue 5 Gyr ago).

- Do we have alpha-enhancement in the outer disk? (Sestito 2008, Hayden 2015, Magrini 2017)
- O and Mg different channels→ different trends→ confirmed by APOGEE (Donor+ 2018)
- O from massive stars: no migration, but impact of bar driven radial gas flow (R<6Kpc)
- [alpha/Fe] is an average value (Magrini+2017)

Young OC metallicity gradient

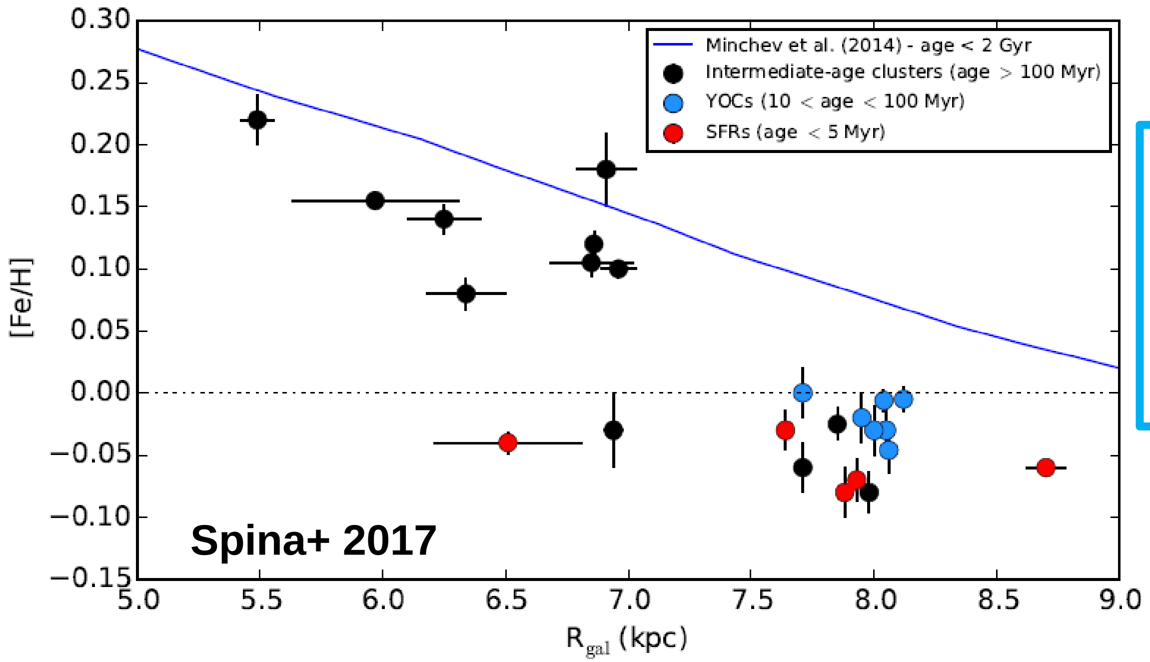


Fig. 8. Radial metallicity distribution of regions younger and older than 100 Myr compared with the model of Minchev et al. (2014) for the age interval between 0 and 2 Gyr including radial migration (blue line).

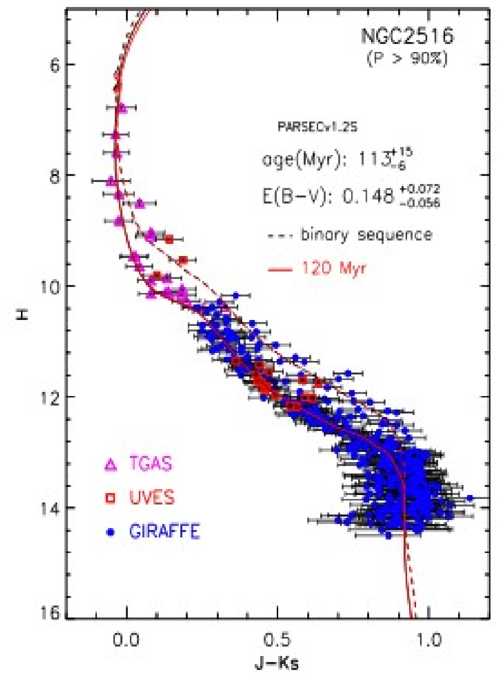
- Gradient flattening with time
- Migration?

Quillen+2018, Anders+2017

Ocs Parameter revision

- Parallax-Pms revision for 150 OCs in the inner 2 Kpc in DR1 and 1200 in DR2 (Cantat-Gaudin+2018)
- Ages for 80 Ocs (Gaia collab, van Leeuwen+, 2017, 2018 Cantat+2018)
- Upmask(Krone-Martins 2014)
- Gaia+GES for 8 clusters(Randich +2017)

Randich+2017



Cantat-Gaudin+2018

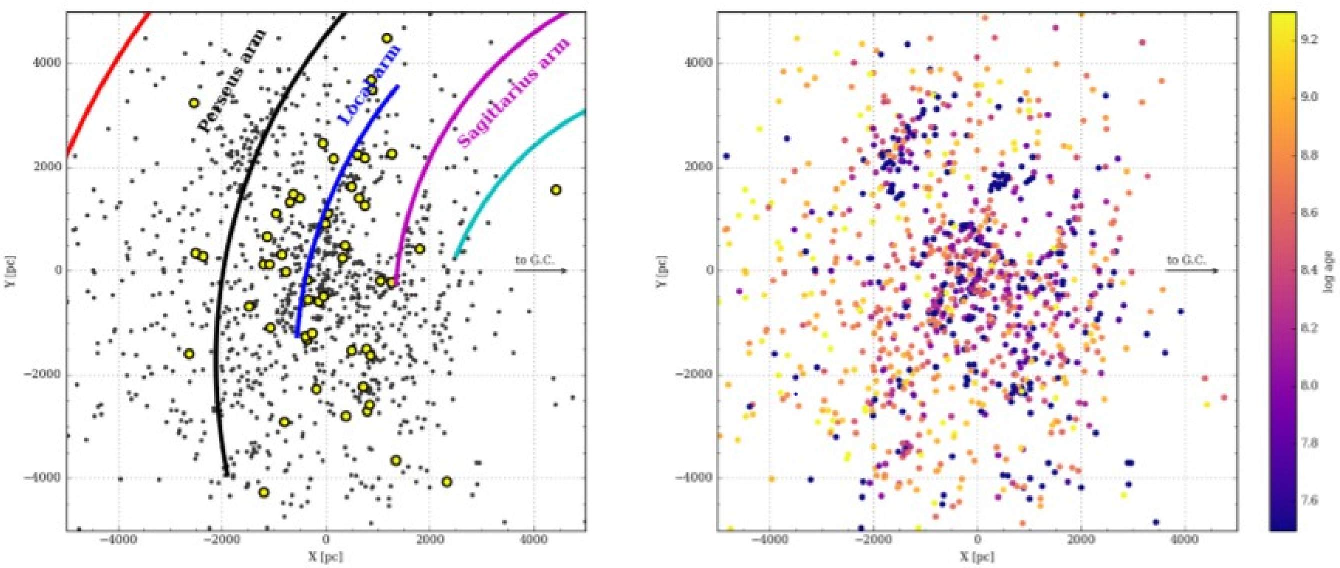


Fig. 11. Left: location of the OCs projected on the Galactic plane, using the distances derived in this study. The yellow dots indicate the objects newly identified in this study. Right: same sample of OCs, colour-coded by age (as listed in MWSC). Superimposed is the spiral arms model of Reid et al. (2014).

See Laia Casamiquela talk

WEAVE Characteristics

Telescope, diameter	WHT, 4.2m
Field of view	2° ⌀
Number of fibers	960 (plate A)/940 (plate B)
Fiber size	1.3″
Number of small IFUs, size	20 x 11″x12″ (1.3″ spaxels)
LIFU size	1.3′x1.5′ (2.6″ spaxels)
Low-resolution mode resolution	5750 (3000–7500)
Low-resolution mode wavelength coverage (Å)	3660–9590
High-resolution mode resolution	21000 (13000–25000)
High-resolution mode wavelength coverage (Å)	4040–4650, 4730–5450 5950–6850

70% of 5 years telescope time; 1 year proprietary time

Primary Science Surveys

- WEAVE GA Goals:
  - To complement Gaia
  - To complement 4MOST , MOONS (in the North)
  - Bridge the gaps in APOGEE footprints
- GA Surveys:
  - LR Halo /LR disk
  - HR halo/HR disk/OC
- Stellar, Circumstellar, and Interstellar Physics (SCIP): 1200 sq deg on the disk (b<3-4 deg) to probe massive stars, ISM, YSO+ Great Cygn Rift star formation
- Characteristics:
  - Continuous sky coverage to sample global phenomena
  - High statistics

WEAVE performances

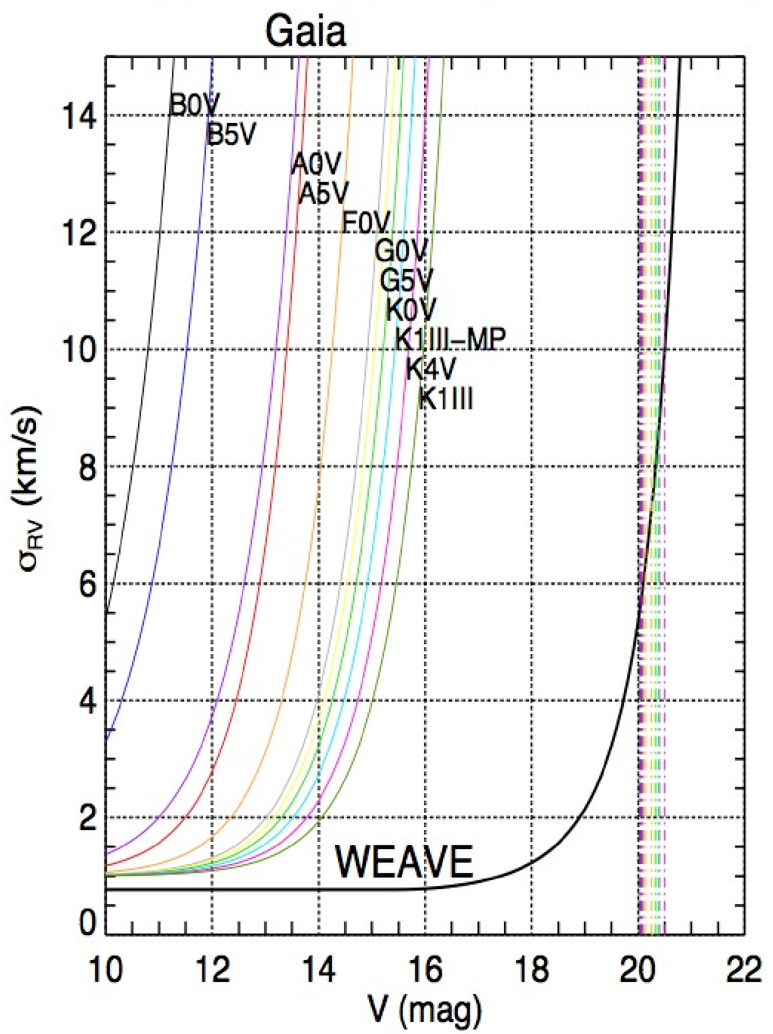
- Surveys to acquire accurate Vr (2 km/s) (and stellar parameters, incl. Metallicity at 0.2 dex)

  15<G<20

  Defined the LR mode of WEAVE:

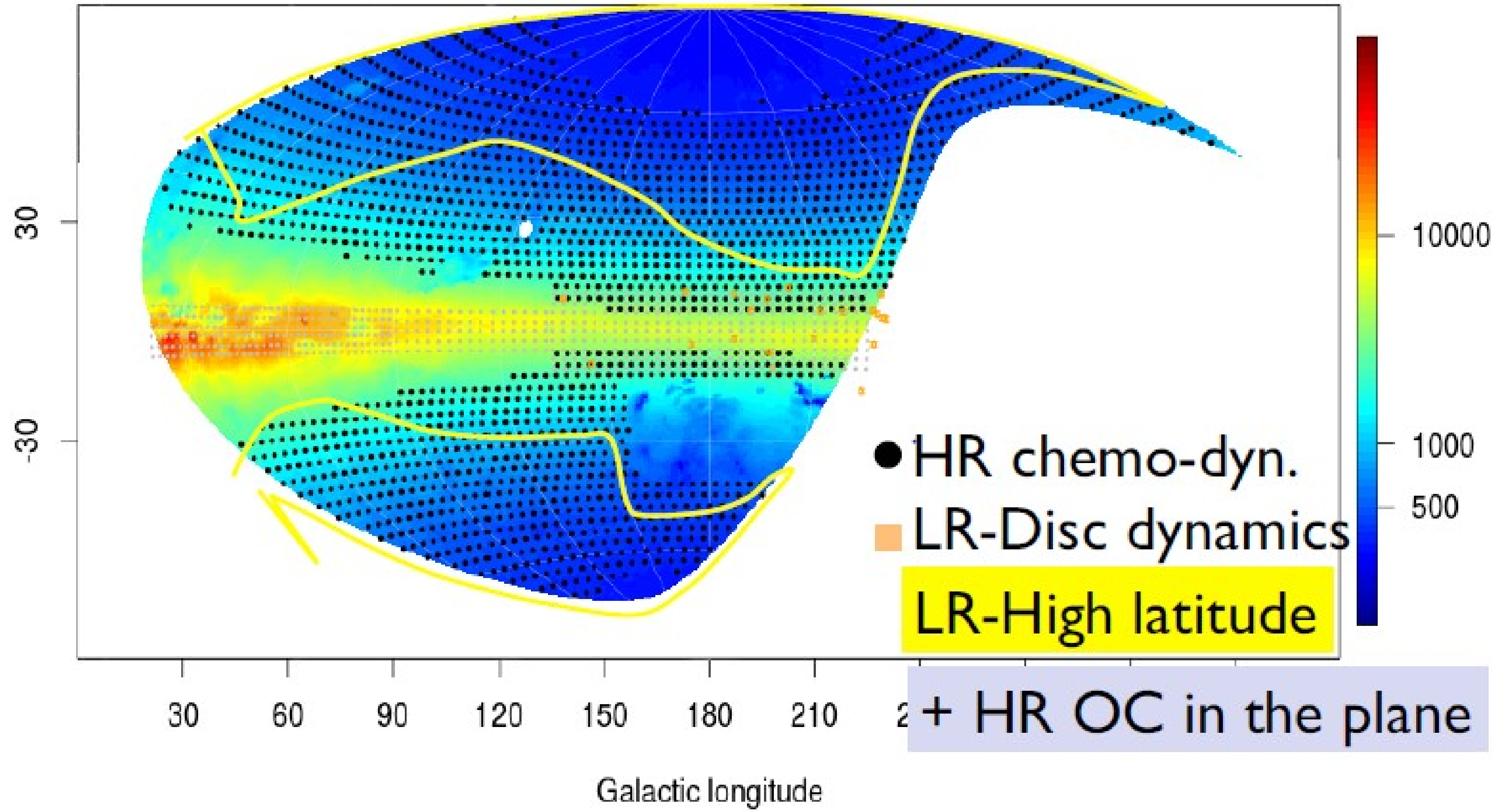
  - R = 5,000 in a wide range [366 – 606] nm + [579 – 959] nm

- Surveys to determine accurate stellar parameters and detailed chemistry(at 0.1 dex) for G>11-17
  - Defined the HR mode of WEAVE:
  - R = 20,000 in two windows [404 – 465] nm or [473 – 545] nm + [595 – 685] nm
  -



R=5000

WEAVE GA at glance



WEAVE - GA ~3-4 million stars to unravel the MW history !

LR disk: |b|<6 -1.5x10⁶ stars
LR Halo: 10,000 sq deg

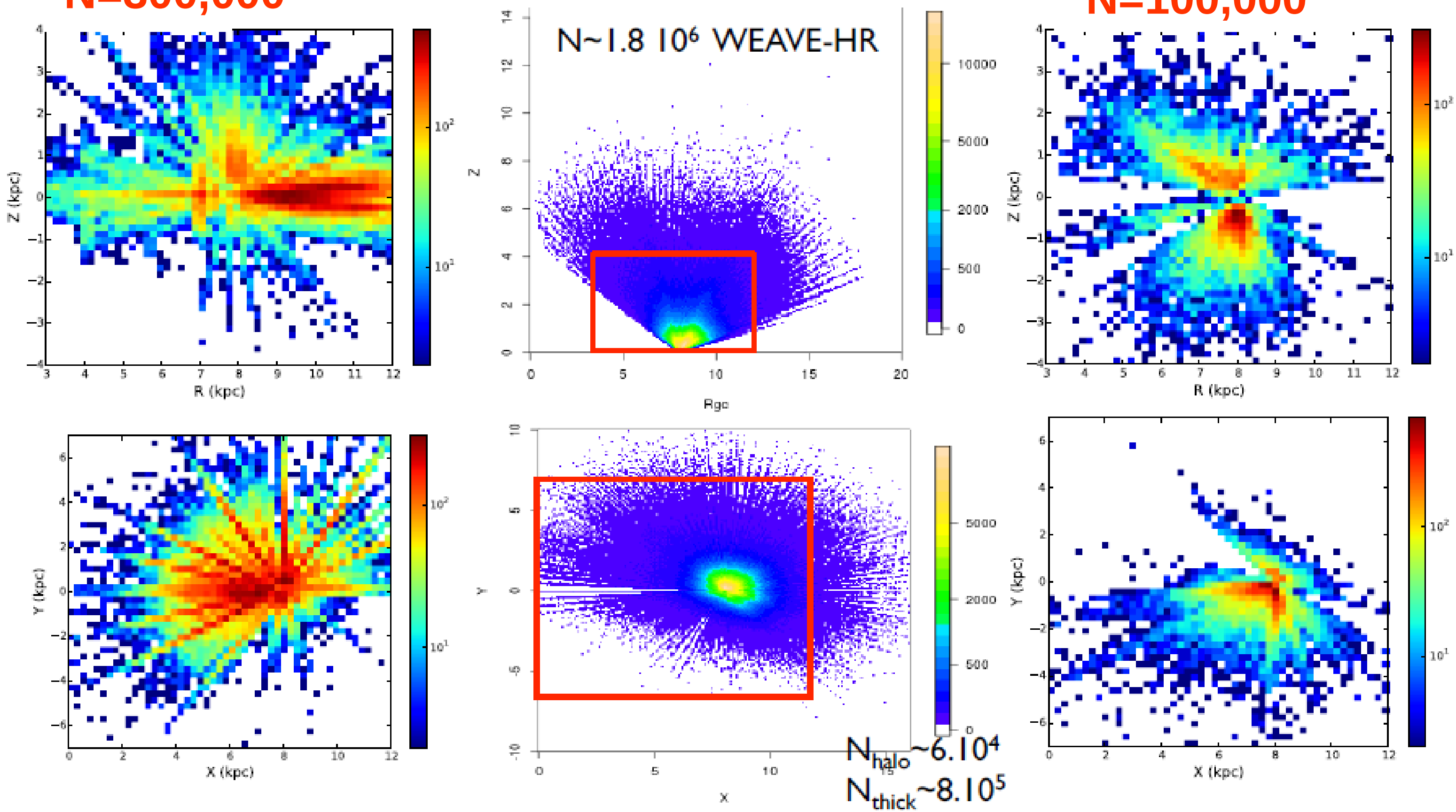
HR disk: 1,800 deg2 with 15<|b|<30° to insure coverage of discs+ **HR halo**:5000 deg2

WEAVE HR in contest

APOGEE - WEAVE - GES

N=300,000

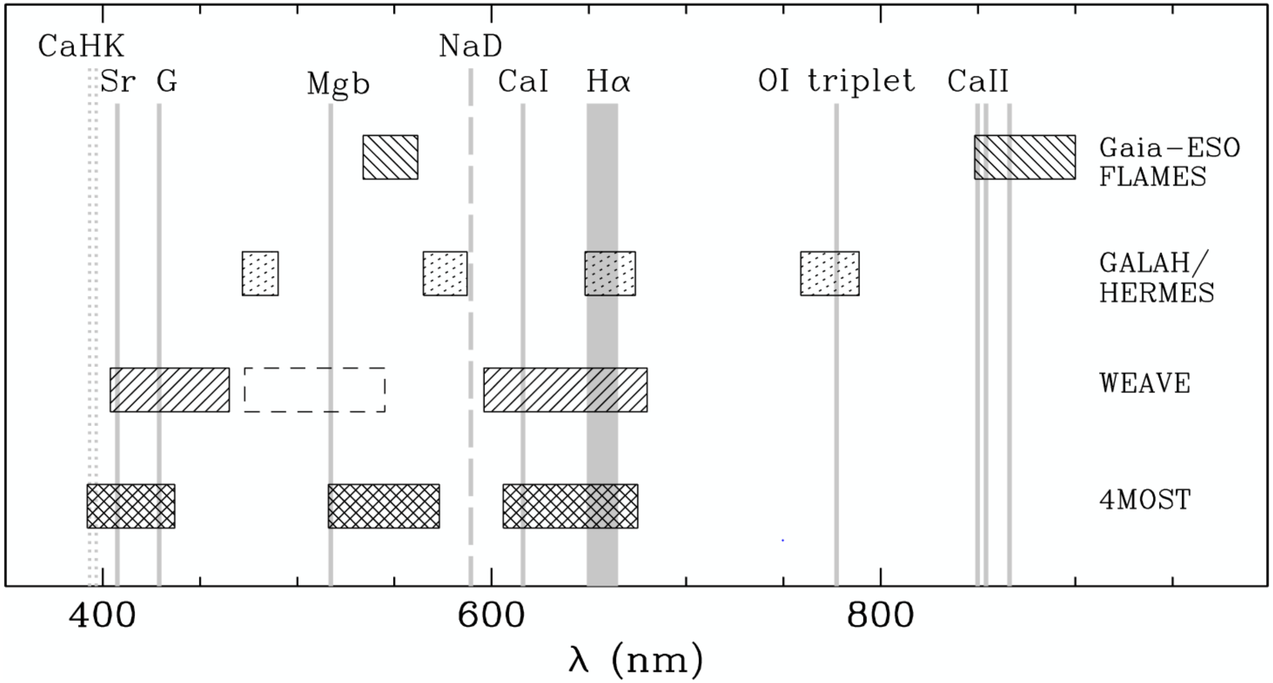
N=100,000



APOGEE WEAVE GES

Kordopatis+ 2016

HR WEAVE & 4MOST

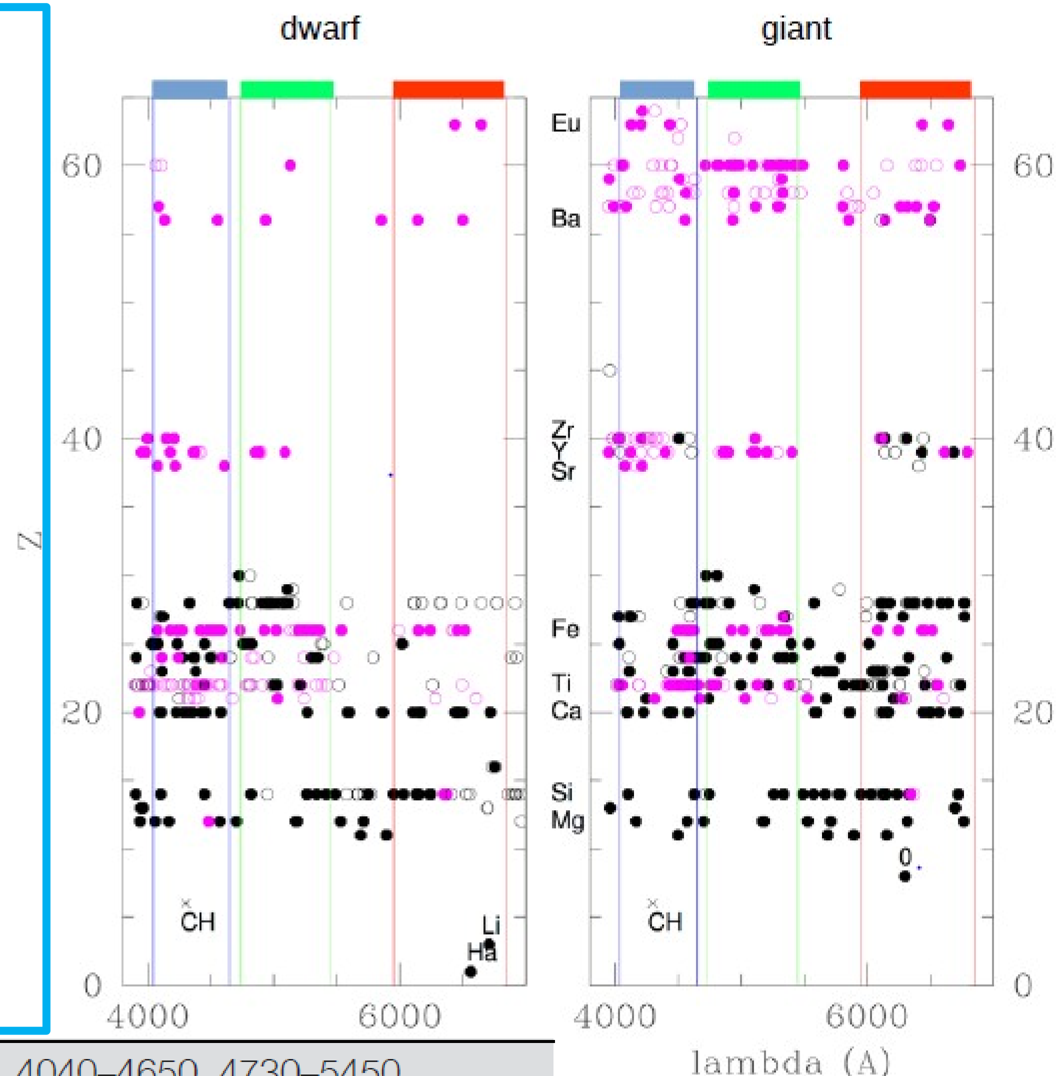


Feltzing 2018

- WEAVE – 4MOST excellent complementarity
- 4MOST 2 LRH and 1HR (3 passbands)

WEAVE HR products

- WEAVE can measure stellar paramete
   and individual abundances in all mair
  nucleosynthetic channels to V=16, i.e.
  closely matching the Gaia's most
  precise   sphere (distances, ages)
- Teff, log(g), Vrad, Vsini
- Nucleosynthetic chanels :
  - Lithium → young objects
  - iron peak (Fe, Ni, Cr, Co, Zn),
  - alpha elements (C, Mg, Si, Ca, [OI …),
  - neutron-capture slow and rapid elements (Zr, Y, Sr, Ba, La, Nd,Eu),
  - odd elements (Na, Al, Sc)



High-resolution mode wavelength coverage (Å)	4040–4650, 4730–5450 5950–6850

WEAVE Timeline

- Now Operation Rehearsal
- First science light: 2019
- Surveys begin: T0+3 months
- WEAVE main instrument at WHT
- 5 years of WEAVE surveys (70% of available time), plus TAC time (30%) which may also include using WEAVE
- Open time PIs will have full access to WEAVE calibration data

Conclusions

- We are just at the beginning of the scientific exploitation of Gaia
- GES and WEAVE are complements to Gaia and present and upcoming surveys with a strong legacy value